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INTEROFFICE CORRESPONDENCE

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RG Smith Jr

FROM: R. G. Smith, Jr., RMRS, Hydrogeology, x7898

SUBJECT: PRELIMINARY EVALUATION OF VERTICAL GROUNDWATER FLOW IN FAULT ZONES AT THE ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE RGS-012-95

This letter report has been prepared to initially evaluate the potential for vertical groundwater flow along bedrock faults related to point-of-compliance issues in support of the site-wide groundwater strategy program. The report presents several approaches that attempt to evaluate bedrock groundwater flow near faults, including the application of environmental isotope data for tracing upper hydrostratigraphic unit (UHSU) groundwater flow to the lower hydrostratigraphic unit (LHSU).

Approach

Vertical movement of shallow groundwater through upper Laramie formation claystones to the Laramie/Fox Hills aquifer has historically been considered minimal due to the great thickness (300 to 500 feet) and low hydraulic conductivity of the media. This assumption has essentially been confirmed by ten years of intensive hydrogeological investigations which have proven that the extent of vertical hazardous and radiological contamination is, with rare exception, limited to the weathered (and more permeable) shallow bedrock. The recent discovery of several inferred fault zones across the plant has raised the possibility of hydraulic communication between shallow and deeper sections of the upper Laramie formation and possibly the Laramie/Fox Hills aquifer. Although this possibility has not been addressed directly by field investigation, it is believed that the existing density of bedrock wells near faults may shed some light on the vertical groundwater flow conditions in these areas.

It is postulated that the presence of permeable bedrock fault zones can be identified on the basis of various geologic and hydrologic characteristics that contrast with the surrounding undisturbed bedrock. Potential indicators of an increased vertical flux along a bedrock fault zone include:

- an increased depth of weathering in bedrock (downward flow regimes only),
- a distortion of the groundwater flow field near faults,
- evidence of atypical hydrologic activity reflected in well hydrographs,
- higher hydraulic conductivities than normally found for a given rock type,
- an anomalous groundwater geochemical distribution, and
- an anomalous groundwater environmental isotope distribution.

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One drawback to this approach is that there are no wells that are conclusively known to be completed in a fault zone. This drawback is, however, minimized to a certain degree because groundwater flow in a permeable fault zone is expected to affect the hydrologic conditions of undisturbed bedrock near the fault zone in detectable ways. For example, an unweathered bedrock sandstone that is offset by a permeable fault might be recharged by the fault zone and thus exhibit a groundwater geochemical or isotopic signature which is different from undisturbed sandstone strata found elsewhere at the same depth. In this way, nearby wells completed in deeper sandstones would be capable of detecting the influence of the fault without having to directly monitor the fault zone.

Of the above listed indicators, evaluations of hydraulic conductivity and hydrograph responses have not been attempted due to limitations imposed by the data sets. In the case of hydraulic conductivity, a condition of the analysis requires that a set of wells be completed in the fault zone. Interpretation of hydrographs from many unweathered bedrock wells is hampered by sampling-induced choppiness in water level response that completely obliterates the subtlety of natural fluctuations. An evaluation of groundwater geochemistry was also not attempted because of the time involved with the analysis, and advantages offered by environmental isotopes for this type of hydrological problem.

Geologic Considerations

Geological observations relevant to an understanding of groundwater occurrence in unweathered bedrock and fault zones have been compiled and summarized by F. Grigsby (see attached memorandum dated November 1, 1995). This information points to the possible importance of fractures and faults in controlling groundwater flow to depths of 150 feet in the bedrock. The potential for deeper vertical flow to the Laramie/Fox Hills aquifer also apparently exists based on fault displacement observed in the aquifer along the Indiana Street shallow high resolution seismic survey line.

Bedrock Weathering

The depth of weathering in shallow bedrock is potentially an important characteristic that, in favorable hydrogeologic settings, can provide information on vertical groundwater circulation and movement. Weathering profiles are controlled by a complex interrelationship of many physical and chemical factors which indirectly reflect permeability variations in the recharge area of an aquifer or aquitard. In areas of downward groundwater movement in bedrock, such as typical of the hillslope and upland areas of RFETS, it is hypothesized that a greater depth of weathering would be observed along hydrologically active fault zones as a result of the increased vertical permeability created by the fault. Indicators of past or present hydrologic activity along faults often include oxidized or mineralized slip surfaces that are easily distinguishable in core samples. The absence of a deeply weathered zone near faults would imply that downward vertical movement of groundwater is minimal relative to the surrounding undisturbed bedrock.

The surface configuration of unweathered bedrock is illustrated in Plate 5-11, Elevation Map Showing the Base of Weathered Bedrock, of the 1995 Geologic Characterization Report. Dense borehole coverage near faulted areas is generally limited to only a few areas of the plant (solar ponds, Building 371 and OU2 areas). In these areas there appear to be no anomalous weathering patterns or trends that suggest a correlation with fault occurrences. The base of the weathered bedrock surface in these areas more closely resembles the bedrock surface or pattern of the Arapahoe No. 1 sandstone. These observations lend support to the contention that faults

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are not significant conduits for groundwater flow to deeper sections of the Laramie/Fox Hills formation.

Potentiometric Head and Hydraulic Gradient Considerations

It is well known that faults can affect groundwater movement as reflected by local alterations in the patterns of both the horizontal and vertical potentiometric head distributions of aquifer and aquitards. In an aquitard, faults acting as barriers would likely only affect groundwater movement in cases where the fault orientation is horizontal to near-horizontal given the fact that groundwater flow in aquitards is predominantly vertical. Little effect in the horizontal or vertical potentiometric configuration of the aquitard would be expected near a vertical barrier fault. Wells completed in zones of lateral groundwater flow (i.e. permeable sandstones) contained within the aquitard would, however, reflect flow field distortions caused by the fault.

Permeable fault zones would act as a source or sink for groundwater flow depending on groundwater recharge conditions existing along the fault subcrop. The hydrologic influence of a permeable fault zone which recharges deeper permeable strata (the situation expected at RFETS) would probably be reflected by abnormally high potentiometric heads in wells that monitor either the fault or connected permeable sandstones.

Analysis of the potential effects of faults on bedrock groundwater flow using the potentiometric head distribution at RFETS is actually quite complicated because of the number of factors which contribute to an understanding of vertical groundwater flow. The principal factors that govern bedrock groundwater flow include the permeability distribution, recharge conditions of overlying surficial deposits, and topography. An example of the complexity involved with using a potentiometric approach for evaluating groundwater movement along faults is illustrated in Figure 1 (segment of Plate 16, *Regional Hydrogeologic Cross Section G-G'*, of the 1995 Hydrogeologic Characterization Report). In this figure, equipotential lines and flow directions are presented in a parallel direction to alluvial groundwater flow and orientation of the piedmont ridge occupied by the plant, but normal to the direction of most faults. The change in vertical flow direction and increase in gradient depicted near two faults in the eastern half of the section lead to a first impression that faulting may have a localized impact on groundwater flow. The configuration of equipotential lines in these areas indicate a steepening of bedrock hydraulic gradients east of the faults. Near the eastern most fault, the contour configuration and lower hydraulic gradients suggests the existence of a potential recharge source. These possibilities are critically examined in further detail in the following discussion.

Interpretation of the vertical groundwater flow regime in Figure 1 (and Plate 16) requires an acknowledgement on behalf of the observer that the vertical scale has been exaggerated by a factor of 10. This exaggeration greatly affects the depiction of contour angles in the bedrock which, at true scale, are virtually flat. Bedrock groundwater flow is therefore predominantly vertical in a downward direction even in areas represented by the steepest equipotential contours. Consideration of the exaggerated scale cross section also gives the misleading impression that wells are located close to the faults when in fact all wells in the cross-section are located at least several hundred feet or more away. Adequate well coverage is thus considered to be lacking in the areas most likely affected by faulting.

The hydrogeologic setting of this area of the plant is an important variable that must be considered when interpreting the potentiometric distribution of the bedrock shown in Figure 1. This area of the plant is located within a discontinuously saturated section of the Rocky Flats alluvium as presented in the 1995 Hydrogeologic Characterization and OU2 RI/RFI reports. The irregular distribution of groundwater in the alluvium and Arapahoe No. 1 sandstone will similarly result in irregular recharge patterns in the bedrock. Aerial exposure of the piedmont ridge caused by deep dissection of the alluvial fan and underlying bedrock by Woman and South Walnut Creeks, combined with a limited source of alluvial recharge, is expected to promote a greater degree of drainage in the bedrock of this area compared to the undissected and continuously saturated alluvial areas of the plant located to the west. This setting would result in an irregular distribution of bedrock potentiometric heads and increased hydraulic gradients starting at the neck in the ridge located near the pondcrete storage area and extending eastward to the end of the ridge. Evidence for this interpretation is provided by the western most fault (fault 2 not shown in Figure 1) which is situated in a continuously saturated area that is away from the fan margin, but is shown to exhibit no unusual distortions in either equipotential contours or hydraulic gradients. Given the complexity of the hydrogeologic setting, there is no potentiometric evidence in Figure 1 that strongly supports a fault explanation for the observed equipotential contour configuration. As mentioned previously, the influence of a permeable fault on groundwater flow in an aquitard would mainly be limited to the fault zone and any offset permeable sandstone beds. The extent of potentiometric influence reflected near the east fault (fault 4) is intuitively greater than would be expected for sandstones with hydraulic conductivities in the 10^{-6} to 10^{-7} cm/sec range (results from wells 46692, 46792, 46892, and 2887 located next to the fault). This interpretation is supported by the environmental isotope data presented in the next section.

Environmental Isotopes

Environmental isotopes are often used as tools in hydrological investigations to trace and evaluate the history of water movement. The isotopes most commonly used in hydrological investigations include the naturally-occurring light stable isotopes of hydrogen (^{1}H and ^{2}H) and oxygen (^{16}O and ^{18}O), and tritium (^{3}H), the radioactive isotope of hydrogen. These isotopes combine to make up various forms of the water molecule - the heavier forms of which occur in relatively small amounts in the hydrosphere. Natural and man-made variations in the relative abundance of these isotopes caused mainly by various physical processes in nature allow these isotopes to be used as tracers in the hydrological environment. Tritium is of special interest because it can provide information on the relative age of the groundwater. Presentation of the concepts and terminology used in isotope hydrology is provided in Section 7.0 of the 1995 Groundwater Geochemistry Report.

Vertical stratification of ^{2}H and ^{18}O isotopes in groundwater at RFETS was first reported in the 1995 Groundwater Geochemistry Report. Generally, groundwater occurring deeper in the bedrock has an untritiated, heavier (less negative) stable isotope signature compared to shallower groundwater which is typically tritiated and consistent in isotopic character to that of present day precipitation. This stratification is observed plant wide and is consistent with a significant change of climatic or recharge conditions that resulted from recharge occurring over an extended period sometime before 1952. The difference in isotopic contents with depth combined with the prevailing downward movement of groundwater in the bedrock beneath the plant offers an opportunity to further evaluate potential vertical groundwater movement in the vicinity of faulted bedrock areas. It is hypothesized that wells completed in unweathered bedrock and located near hydrologically active faults would yield groundwater with isotopic signatures similar to that of shallower groundwater systems. Many unweathered bedrock wells sampled for environmental isotopes are located near faulted areas at the Solar Ponds and OU2.

Presentation of the vertical distribution of ^{18}O and tritium in groundwater plotted against the well intake midpoint depth has been accomplished using the bedrock surface as a datum as shown in Figures 2 and 3. For wells with partially submerged screens, the midpoint is based on an upper boundary defined by the water table elevation. The pattern revealed by the ^{2}H data is essentially identical to that of ^{18}O and is, therefore, not presented as part of this discussion. Table 1 contains the updated database used for generation of the figures.

Tritium

As illustrated in Figure 2, the tritium concentrations of shallow groundwater mainly range from about 10 to 50 tritium units (T.U.) with plant-derived (technogenic) sources located at the solar ponds accounting for the values above 50 T.U.s. Detectable tritium concentrations in known hydrologically active bedrock zones, such as the Arapahoe No. 1 sandstone, clearly reflect the influence of recent (post 1952) recharge. The incidence of detectable tritium concentrations in bedrock wells drop off rapidly with depth, and is sharply reduced below the weathered zone. Of the 52 unweathered bedrock wells tested for environmental tritium, only seven contained tritium in detectable concentrations (detection limit = 0.8 T.U.). This distribution is consistent with the viewpoint that the uppermost unweathered bedrock is predominantly hydrologically inactive as supported by the calculated steep vertical hydraulic gradients and low hydraulic conductivity of aquitard materials.

Tritium is viewed as the most effective environmental isotope tracer for evaluating groundwater flow especially in areas such as the solar ponds where tritium contamination has raised the initial source concentrations substantially above natural levels. Low concentrations of tritium were detected in unweathered bedrock wells 1486, 2386, 2287, 4587, P208889, P416989, and 23193, ranging from 0.8 to 1.9 T.U.s. Except in the case of well 2386, there is no information that would implicate poor well construction as an explanation for the reported tritium values in these wells. The results from well 2386 are considered to be potentially suspect based on experience with flush mount completions at other sites. Sunken well covers are sometimes prone to filling with precipitation and surface runoff, both of which contain levels of environmental tritium that are significantly elevated relative to the deep groundwater. The remaining wells are scattered throughout the plant, including wells P208889 and 4587 which are located near faults 3 and 4, respectively.

None of the unweathered bedrock wells in the solar pond area contain appreciable tritium with all but two (well P208889 = 1.0 T.U.; well 1486 = 0.8 T.U.) containing non-detectable amounts. At 86 feet below the bedrock surface, the screen midpoint of well P208889 is situated deeply in the unweathered zone (silty claystone) about 21 feet above the midpoint of well 3987. The presence of tritium in this well proves that at least a component of water produced by the well is of relatively recent age. Examination of the P208889 hydrograph indicates that water levels never fully recover after quarterly sampling events. This slow response is indicative of low hydraulic conductivity conditions which is more conducive to vertical rather than lateral groundwater flow. The occurrence of low tritium levels in other unweathered bedrock wells which are apparently unassociated with faults (P416989, 2287 and 23193) raise the possibility that detectable tritium observed in well P208889 is fracture, but not fault-related. Fracturing, if present, is probably limited in importance, but shows some hydrologic connection to the shallow groundwater system.

Well 1486 is located near fault 3 in the Walnut Creek drainage northeast of the solar ponds. A review of the lithologic log for well 1486 indicates the presence of weathering in the sandstone completion zone. Consequently, it is properly classified as a weathered bedrock (UHSU) well. Faulting is not believed to influence groundwater flow in bedrock at this location because of it's position away from the fault trace. Supporting evidence for this conclusion includes unweathered bedrock well 1686, located at the fault trace in Walnut Creek, which does not contain detectable tritium.

Well 4587 is completed in a relatively permeable sandstone (6.8 x 10^{-5} cm/sec) located near fault 4. The hydraulic conductivity of the sandstone suggests the possibility of lateral groundwater flow. If continuous, this sandstone is projected to subcrop at or just above stream level and thus represents a potential bedrock discharge area to the Woman Creek drainage. At 1.6 T.U., the tritium content of this well indicates a limited amount of communication with shallower groundwater that may be fault-related. The lack of deep well data in this area prevents further analysis of the possible role of fault 4 in controlling groundwater flow. Conceptually, it is also possible that tension fracturing caused by valley stress relief could contribute to vertical groundwater movement in hillside areas.

Water levels in well 4587 fluctuate over a one foot range at intervals that appear to be approximately related to shallow seasonal variations. These variations confirm that the sandstone has a limited degree of hydraulic connection to the shallow groundwater system.

Oxygen-18

The pattern of shifting delta ^{18}O values toward heavier contents with depth in the unweathered zone shown in Figure 3 coincides with a shift to untritiated groundwater as illustrated in Figure 2. This contrast in isotope content, combined with a general knowledge of the vertical groundwater flow direction, permits oxygen-18 (and deuterium) to be used as a tracer for evaluating groundwater movement near fault zones. Under favorable circumstances, oxygen-18 can provide hydrologic information related to the origin of the water not otherwise provided by tritium.

The results of groundwater delta ^{18}O analyses indicate that surficial deposits and weathered bedrock have virtually identical isotope signatures compared to heavier values in unweathered bedrock. These data confirm the conclusion drawn from the tritium profile that groundwater flow in the aquitard below the weathered zone is generally sluggish and poorly connected to the shallow flow system. The significance of the data and implications for groundwater flow are discussed in the following paragraphs.

In the absence of an evaporated water recharge source, systematic changes in groundwater isotope contents along flow paths are usually associated with past changes in climate or recharge conditions (i.e. isotope fractionation during condensation and evaporation is temperature dependent). The correspondence with tritium data suggests that a relatively recent environmental change toward cooler conditions (or more northerly moisture source) occurred sometime before 1952 (pre-plant operations). This relationship holds for all but four wells (3087, B304289, B304989, and 57594) which are located in valley bottoms (see figure) and contain untritiated, isotopically light groundwater. At first glance, these data seem to indicate that hydrologic communication with shallower groundwater flow systems is a possibility. However, consideration of the valley floor setting of these wells, combined with the tritium data and observed or inferred upward vertical bedrock groundwater gradients at these locations, suggest that unweathered bedrock groundwater beneath the valley floors may represent the terminal end of local flow paths that initiate in the adjacent upland areas. This interpretation would mean that the valley floor unweathered bedrock groundwater is actually older than unweathered bedrock groundwater found elsewhere in wells located beneath the hillslope and upland areas of the plant. The timing of these hypothesized climatic shifts have not been synchronized against local climatic records, hydraulic age calculations, or other paleoenvironmental indicator data that might help constrain the age of groundwater in the upper LHSU.

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Having accounted for the isotopically light values found at depth in the unweathered bedrock, there appear to be no delta ^{18}O data that indicates significant vertical groundwater movement in the aquitard. Interpretation of the delta ^{18}O data is subject to the same set of limitations that apply to the tritium data, i.e. the uncertainty associated with the placement of any well intakes in fault zones or associated permeable sandstone beds.

Conclusions

Considering the results of the preliminary analyses presented above, the available hydrogeologic and isotopic evidence suggests that faults are not significant conduits for downward vertical groundwater flow to deep aquifers. Evidence of limited hydraulic communication between UHSU and LHSU groundwater was found to exist in some wells, but these occurrences do not present a consistent pattern with known fault locations. Isolated fractures in unfaulted bedrock, as opposed to fault zone fractures, are implicated as the most likely mode of transport for UHSU groundwater to reach unweathered bedrock. Fault-related groundwater flow cannot, however, be entirely eliminated based on the results from well 4587 and the uncertainty related to the adequacy of monitoring well coverage in fault zones. Due to the thickness and claystone nature of the aquitard, it is likely that fault zones will become more impermeable with depth thus reducing the potential for any shallow groundwater flow to the Laramie/Fox Hills aquifer.

Field investigations designed to assess vertical groundwater flow along fault zones would be expensive and time consuming. It is projected that five to ten 150 foot deep boreholes per site would be required for fault delineation due to the difficulty involved with defining fault geometry and targeting well completion intervals. The available hydrologic evidence does not appear to justify this type of expenditure which, based on previous estimates, could run into the multi-hundred thousand to million dollar range.

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Attachments:
1.) Memorandum of 11/1/95 Subject: Indicated Faults at FETS
2.) Figure 1
3.) Figure 2
4.) Figure 3
5.) Table 1-Isotopic Compositions of Groundwater

cc:
F. C. Grigsby
T. P. Lovseth
ERPD Records (2)